N94-30624

209931
P-16

Report: Linkages between Terrestrial Ecosystems and the Atmosphere

Francis Bretherton, Robert E. Dickinson, Inez Fung, Berrien Moore III, Michael Prather, Steven Running, and Holm Tiessen

Introduction

The possibility of major changes in the global environment presents a difficult task to the scientific research community: to devise ways of analyzing the causes and projecting the courses of these shifts as they are occurring. Purely observational approaches are inadequate for providing the needed predictive or anticipatory information because response times of many terrestrial ecosystems are slow, and there is a great deal of variation from place to place. Furthermore, many important processes, such as soil processes, cannot be measured directly over large areas. We need models to express our understanding of the complex subsystems of the earth, how they interact, and how they respond to and control changes in climate and biogeochemical cycles.

The primary research issue in understanding the role of terrestrial ecosystems in global change is analyzing the coupling between processes with vastly differing rates of change, from photosynthesis to community change. Representing this coupling in models is the central challenge to modeling the terrestrial biosphere as part of the earth system.

Terrestrial ecosystems participate in climate and in the biogeochemical cycles on several temporal scales. Examples of processes that operate on short time scales (i.e., less than days) are the metabolic processes responsible for plant growth and maintenance, and certain microbial processes associated with dead organic matter decomposition. The associated energy balance is also affected at short time scales.

CONT

Some of the carbon fixed by photosynthesis is incorporated into plant tissue and is delayed from returning to the atmosphere until it is oxidized by decomposition or fire. This slower (i.e., days to months) carbon loop through the terrestrial component of the carbon cycle, which is matched by cycles of nutrients required by plants and decomposers, affects the increasing trend in atmospheric CO_2 concentration and imposes a seasonal cycle on that trend. Moreover, this cycle includes key controls over biogenic trace gas production. The structure of terrestrial ecosystems, which responds on even longer time scales (annual to century), is the integrated response to the biogeochemical and environmental constraints that develop over the intermediate time scale. The loop is closed back to the climate system since it is the structure of ecosystems, including species composition, that sets the terrestrial boundary condition in the climate system through modification of surface roughness, albedo, and, to a great extent, latent heat exchange.

These separate temporal scales contain explicit feedback loops which may modify ecosystem dynamics and linkages between ecosystems and the atmosphere. Consider again the coupling of long-term climate change with vegetation change. Climate change will affect vegetation dynamics, but as the vegetation changes in quantity or type of structure, this may feed back to the atmosphere by changing water, energy, and gas exchange. Biogeochemical cycling will also change, altering the exchange of trace gas species and nutrient availability. The long-term change in climate, resulting from increased atmospheric concentrations of greenhouse gases (e.g., CO_2, CH_4, and nitrous oxide [N_2O]) will further modify the global environment and potentially induce further ecosystem change. Modeling these interactions requires coupling successional models to biogeochemical models to physiological models that describe the exchange of water, energy, and biogenic trace gases between the vegetation and the atmosphere at fine time scales. There does not appear to be any obvious way to allow direct reciprocal coupling of atmospheric general circulation models (GCMs), which inherently run with fine time steps, to ecosystem or successional models, which have coarse temporal resolution, without the interposition of physiological canopy models. This is equally true for biogeochemical models of the exchange of carbon dioxide and trace gases. This coupling across time scales is nontrivial and sets the focus for the modeling strategy.

Scales of Interactions

Based on current model structures, atmosphere-biosphere interactions can be captured with simulations operating with three char-

acteristic time constants (Figure 1). The first level represents rapid (seconds-day) biophysical interactions between the climate and the biosphere. The dynamics at this level result from changes in water, radiation, and wind and accompanying physiological responses of organisms. Dynamics at this level occur rapidly relative to plant growth and nutrient uptake, and far more rapidly than species replacement can occur. Simulations at this level are required to provide information to climate models on the exchange of energy, water, and CO_2. Tests of this level of model can be accomplished using experimental methods including leaf cuvettes, micrometeorological observations, and eddy correlation flux measurements.

The second level captures important biogeochemical interactions. This level captures weekly to seasonal dynamics of plant phenology, carbon accumulation, and nutrient uptake and allocation (Figure 1). Most existing models at this level use integrative measures of climate such as monthly statistics and degree-day sums. Changes in soil solution chemistry and microbial processes can be captured at this level for calculation of trace gas fluxes. Primary outputs from

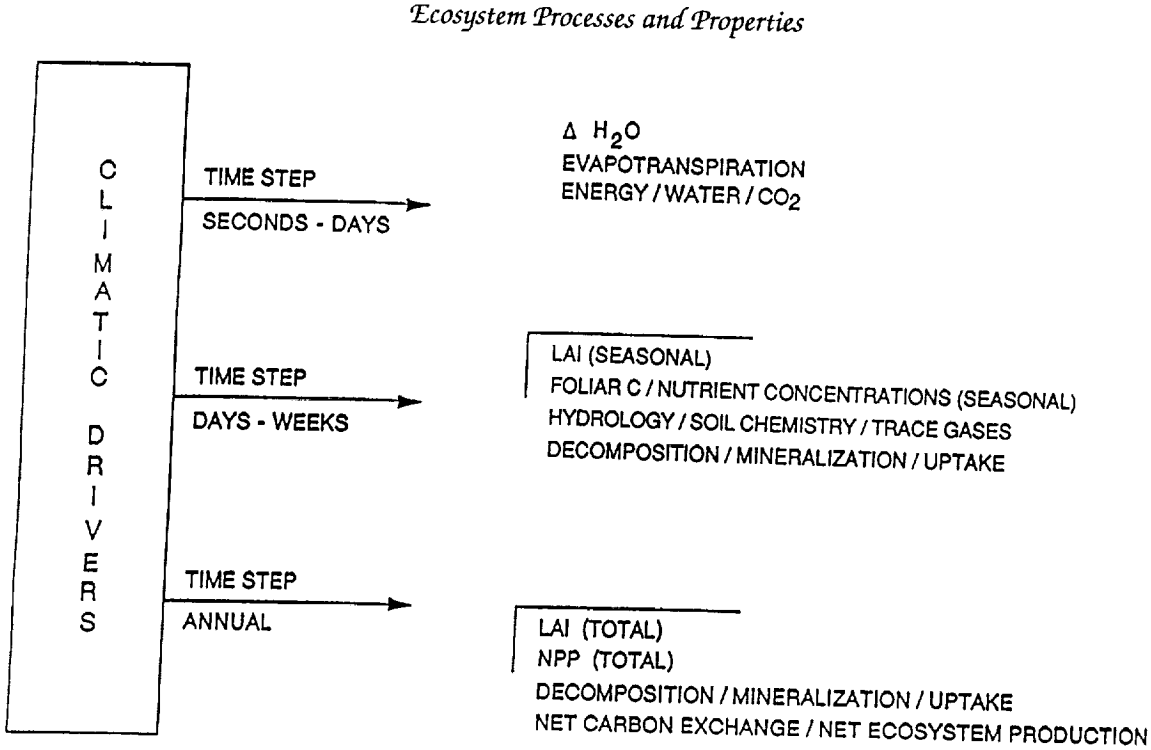

Figure 1. Scales of interaction between climatic interactions and ecosystem properties.

this level of model are carbon and nutrient fluxes, biomass, leaf area index (LAI), and canopy height or roughness. This level of model is usually tested in field studies with direct measurements of biomass, canopy attributes, and nutrient pools or fluxes.

A third level of model represents annual to decadal changes in biomass and soil carbon (net ecosystem productivity, carbon storage) and in ecosystem structure and composition (Figure 1). Inputs are statistical distributions of climate variables and calculated indices summarizing the effects of climatic conditions on biomass accumulation and decomposition. The outputs include ecosystem element storage, allocation of carbon and other elements among tissue types, and community composition and structure. Such models are currently based either on individual organisms or on species correlations with environment. The former are difficult to apply at large scales because of computational and data requirements, and considerable work will be required to develop large area implementations. This type of model is validated using a combination of process studies, as described above. These processes need to be integrated and validated in comparative studies to derive annual fluxes. The community composition and population dynamics aspects of these models are often validated using paleodata.

There are two scales of spatial resolution. At fine resolution, climate model results are used to drive regional-scale ecosystem process models, which are rather mechanistic. Much higher spatial resolution than currently available is needed for terrestrial climate variables, particularly for complex terrain (e.g., mountain ranges). Next-generation GCMs, such as the community climate model version 2 (CCM2) from the National Center for Atmospheric Research (NCAR) (with 250 x 250 km resolution), will improve on this problem, but only in a modest fashion, and will not satisfy all needs of terrestrial modeling. Development of nested model techniques and greater computing power will be needed to produce climate-related results in the range of resolution (10–20 km) required by ecosystem process models. Spatial distribution of precipitation is most critical, and improved surface topographic definition (as done in CCM2) is a critical step in improving orographically related precipitation.

At the coarser scale required for the operation of global terrestrial vegetation models, GCM grid scale is nearly adequate, although improvements are highly desirable. However, any dynamic process model of global vegetation can be linked to key satellite-derived variables, such as advanced very high resolution radiometer (AVHRR) vegetation index data and the normalized difference vegetation index (NDVI), that provide reference characteristics of the land surface. Current global NDVI-based land cover maps have a resolution of

about 4 x 4 km; however, for many global applications these data could be aggregated to near GCM cell scales. It is important that future GCMs be able to interactively incorporate satellite data for regular redefinition of surface albedo and of vegetation characteristics related to evapotranspiration (ET), such as LAI. Additionally, regular monitoring of changing land cover and land use will be important.

Atmospheric GCMs tend to simulate mean atmospheric conditions. However, many terrestrial processes, such as biome replacement, are triggered by occasional extreme events. Although these events do not have global significance, they are of unsurpassed importance regionally. The meteorological conditions that triggered the 1988 fires at Yellowstone National Park will have regional consequences for the next century. Spring frosts, which occur early in the growing season; multiple years of successive drought; floods; and hurricanes are other examples of extreme meteorological events that have potentially significant ecological ramifications. Some lakes in central Australia only contain water a few times per century, when extreme precipitation events occur. The utility of augmenting GCM results with regional climatological statistics, as suggested by F. Bretherton in the appendix to this chapter, may be the most reasonable way of providing this data.

Specific Variables Linking the Atmosphere with the Terrestrial Ecosystem

Precipitation

Simulation of precipitation requires high spatial resolution (10–50 km), particularly in complex terrain. Minimum event resolution is around 3 mm for regional process simulations. At least daily time resolution is essential to differentiate between precipitation that is intercepted by vegetation canopies and evaporated immediately and precipitation that enters the soil rooting zone, with a subsequent residence time of days to months. Also, interception and evaporation have only physical controls; the dynamics of soil water uptake are controlled by plant physiology in concert with physical drivers.

There are several ways to reduce uncertainties of local precipitation from coarse-resolution models:

- Empirical relationships can be developed between mean precipitation and other large-scale circulation statistics for the region defined by a GCM grid cell and precipitation data at individual stations within the grid cell (see appendix to this chapter, "A Regression of Atmospheric Circulation to Local Weather"). Such relationships can then be used to extract subgrid-scale precipi-

tation variations from GCM simulations. This is the approach used in standard numerical weather forecasts. However, it is not clear whether such empirical relationships will hold in a changing climate.

- The planned Tropical Rainfall Measuring Mission (TRMM) will allow precipitation to be derived from satellite observations (in the microwave). Limiting its value, TRMM is planned to be an exploratory mission, i.e., of limited lifetime, and it will be focused on the tropics.

- Algorithms are being developed to extract intensities of convective precipitation in the tropics from satellite measurements of outgoing longwave radiation (OLR) at the top of the atmosphere. They employ the fact that colder brightness temperature is correlated with higher convection and more intense rainfall. The approach looks promising, and it should be extended to the rest of the globe. High-resolution (15-minute, ≈20-km) OLR data are in the archives, as are high-resolution precipitation data at river gauge stations (U.S. Geological Survey network); these data are useful for testing the algorithms. If global algorithms can be developed, they offer the possibility of gaining a self-consistent data set for expressing subgrid-scale precipitation in terms of larger-scale variables such as mean precipitation or OLR. It is not known whether the relationships will hold in a changing climate. Looking at year-to-year variations in the relationships may provide a clue, depending on the quality and availability of data sets for regional verification.

- Mesoscale models nested in GCMs (e.g., Dickinson et al., 1989) promise predictive capability for local precipitation. A GCM is run at coarse resolution, and then a high-resolution mesoscale model for a region such as the western United States uses the GCM output as boundary conditions or driving functions and simulates the climate within each grid cell of the region. The usefulness of this approach depends, of course, on whether cloud physics and precipitation dynamics are properly incorporated in the models. For global applications, precipitation with a precision of 10 mm may be acceptable.

Temperature

Canopy-level temperatures are needed to drive evapotranspiration, photosynthesis, and respiration computations, preferably at daily time scales. Various growing season definitions, ecosystem phenology, etc., are best defined either by integrated daily temperatures

(i.e., growing degree day crop forecasts) or by thresholds, e.g., last frost–first frost growing periods. The needed accuracy is about 1°C. Substantial spatial variability within GCM cells is caused by topography (slope, aspect and elevation) and by variability in land surfaces, such as forest vs. cropland, irrigated land vs. desert, and upland vs. wetland. Variability in topography and land cover can be described statistically, rather than by geographically explicit treatments.

Monthly or yearly average temperatures are used to drive models of soil processes, such as decomposition and N mineralization. For these models, soil temperatures at a depth of 10–20 cm are needed, as well as surface or canopy temperatures. Additionally, simplified primary production models, once they have been "calibrated" by daily canopy models, can be used for general global estimates with minimal data requirements. GCM grid cell output of daily maximum and minimum temperatures is very useful for defining continental-scale vegetation phenology and growing seasons.

Atmospheric Deposition of Nutrients

A subset of required precipitation data for terrestrial ecosystems is wet and dry deposition of atmospherically transported chemicals, including nutrients such as the nitrate, ammonium, sulfate, and phosphate radicals (NO_3^-, NH_4^+, $SO_4^=$, and $PO_4^{\equiv}$). Acid rain and air pollutant deposition effects on terrestrial ecosystems have been widely studied. GCMs simulate the physical mechanism of transport of these aerosols, particulate matter, etc., but they do not couple the compounds to measured source fields, and they do not include any of the atmospheric chemistry involved in their transformations. Future versions of GCMs should be able to provide deposition estimates globally.

NO_3^- is deposited from the atmosphere both as nitrate in rainfall and directly as nitric acid (HNO_3). The fractional input from both sources appears to be about equal, as some recent studies of HNO_3 downward fluxes over grasslands have shown. Dry deposition of nitrogen dioxide (NO_2) is less important because of the smaller relative atmospheric abundance. The atmospheric budget of NO_x, which consists of nitric oxide (NO) plus NO_2, is approximately 18.5–89.5 Tg N/yr, as shown in Table 1.

In remote areas, the abundance of HNO_3 is typically 0.1 ppbv or 0.2 Tg N, with an average atmospheric lifetime against rainout of five days. This gives a budget of 50 Tg N/yr (with an uncertainty of at least a factor of two). The lightning source may be dependent on latitude and can be regionally important (Liaw et al., 1990), but will be dispersed since the NO it produces must be oxidized to HNO_3 before deposition. Most of the large emissions associated with urban pollution are observed to decay rapidly (presumably to the nearby areas).

Table 1: Global budget for NO_x

Source	Tg N/yr
Stratospheric input (from N_2O)	0.5–1.5
Lightning	8 (2–20)* [81 ± 65.7]**
Soil sources	8 (1–16)
Fossil fuel burning	21 (14–28)
Biomass burning	12 (1–24)
Total	**18.5–89.5** excluding large lightning values

Logan, 1983; Liu and Cicerone, 1984
*Liaw et al., 1990

Accurate global modeling of the nitrate system is difficult and has only recently been attempted in global chemical transport models (CTMs). The current models cannot be used to predict nitrate input accurately, but in the next few years they are expected to produce a good but incomplete global picture of the NO_x budget. Anthropogenic inputs are expected to dominate near industrial regions.

Ammonia (NH_3) deposition from the atmosphere is most likely to come in the form of ammonium nitrate (NH_4NO_3) or some other neutralized ammonium aerosol. Although elevated concentrations of NH_3 gas have been measured above biologically active "hot spots" (e.g., animal feedlots), concentrations are difficult to detect in the free troposphere. The implication (consistent with the observed abundances of HNO_3 and acidic aerosols) is that NH_3 is removed from the atmosphere in aerosols. (The lifetime against oxidation of the hydroxyl free radical, OH, is greater than 30 days, even in the tropics.) If NH_3 forms aerosols in the boundary layer in the immediate vicinity of where it is emitted, then the most likely effect of ammonia volatilization is the horizontal dispersion of nitrogen.

Ammonia releases are deposited within a few hundred to a thousand km (generally downwind) of their source. Global models for atmospheric NH_3 are not available.

The sources of sulfates deposited to the ecosystem include marine sea salt, photochemically oxidized marine sulfides, and anthropogenic sulfates. (We exclude here volcanic emissions.) In regions where marine sulfide-to-sulfate sources may be important, it is likely that deposition of sea salt sulfates provides adequate fertiliza-

tion. These regions are thus independent of the atmospheric chemistry. Large perturbations to sulfate-limited ecosystems will probably occur only if they are downwind from industrial sources, such as areas with considerable combustion of sulfur-containing fuel or smelting.

For ecosystems that are limited by phosphorus, the only atmospheric source is associated with large dust storms. Such storms are not regular, annual processes, but rather extreme events that cannot be predicted from current atmospheric CTMs. Changes in inputs of phosphorus are likely to be the result of extreme climatic events.

The potential impact of acid rain is proportional to the total flux of hydrogen ions (H^+) both in rainfall and in dry deposition (e.g., HNO_3). Normal rain is acidic: pH's of about 5.5 are due to the solubility of 350 ppm of CO_2 in water. Even in remote regions, organic acids such as formic acid (the result of oxidation of CH_4 and other hydrocarbons) reduce the pH of rainfall to 5 or less. In regions perturbed by large anthropogenic sources of acid precursors (e.g., NO and sulfur dioxide, or SO_2), the acidity of the rain is likely to be below a pH of 4. However, in regions with alkaline soils, the natural dust can neutralize the acidity of rain (pH > 6). Regional acid deposition models have been used to predict H^+ fluxes for part of the United States, but the deposition of H^+ is difficult to predict on a global scale. Significant amounts of acid rain (and deposition) are expected a few thousand km downwind of large anthropogenic sources of NO and SO_2.

Ozone

The interaction between ozone and vegetation is an important link in modeling both the ecosystem and the atmosphere. High local ozone concentrations can be deleterious to vegetation, damaging stomata and affecting evapotranspiration. Currently there are regional models for air quality that predict tropospheric ozone over part of the United States. Many research groups are developing CTMs for global tropospheric ozone, and we may expect such models to contribute to these regional atmospheric-ecosystem models in the next few years. The occurrence of extreme ozone events will still be difficult to predict in the global models.

The destruction of ozone at the earth's surface is an important part of the global budget for tropospheric ozone. Observations show that ozone is removed with high efficiency above regions with active plants. Emissions of NO, N_2O, CH_4, isoprene (C_5H_8), and other hydrocarbons from vegetation and soils play a major role in global atmospheric chemistry.

Humidity

GCMs provide a water mixing ratio in the lowest layer of the model (900–1000 mb, depending on the model). In some boundary-layer models, this can be translated into dewpoint at the canopy surface. Humidity is critical for modeling ET and stomatal response models, but less so for soil carbon or nitrogen cycling except as a component of hydrologic balance. If a spatially and diurnally conservative measure of humidity is used, such as dewpoint or mixing ratio, fairly broad regional average conditions may be adequate. The needed accuracy is $\approx 1°$. However, canopy- or surface-level estimates are needed, as a bulk tropospheric mixing ratio probably underrepresents the near-surface humidity over vegetated surfaces.

Solar Radiation

Incoming shortwave or photosynthetically active radiation (PAR) is very critical for photosynthesis and ET models, although less so for modeling soil processes. Incoming solar radiation is well modeled by GCMs for a molecular atmosphere, but inadequate simulation of clouds and aerosols in current climate models makes this a feature of questionable value. Hourly or daily resolution is needed for photosynthesis and ET models; monthly or annual totals are used in ecosystem dynamics models. It is not critical to partition between direct and diffuse radiation or between total radiation and PAR. Subgrid-scale topographic variability can easily be handled with corrections for slope and aspect. However, subgrid-scale clouds and optical variability are problems.

Wind and Dust

Extreme storms, hurricanes, etc., are important ecosystem disturbance triggers. The recurrence of extreme climatic events determines ecosystem structure to a certain extent. There really is no satisfactory way to simulate extreme winds with a coarse-resolution model. Parameters such as minimal surface pressure may be useful for defining storm existence and perhaps storm tracks. However, an operational diagnostic of maximum winds may not be readily available in GCMs. Average wind velocity is also an important component of evaporation, and daily averages may be adequate for ET estimates. This parameter, average wind velocity, is highly variable and unpredictable in complex topography that is below grid-scale resolution.

Extreme wind conditions are of high importance for dust plumes and soil erosion calculations (which also require soil texture and moisture information). Dust affects soil properties, incident solar radiation, and terrestrial productivity. All of the necessary atmos-

pheric parameters are available in principle in GCMs. However, the current capabilities of the GCMs and our understanding of source functions need significant improvements before useful applications can be made.

Snowpack

Snowpack is a critical available output from GCMs. Snowpack is a major albedo and hydrologic balance determinant and is an important output variable of most GCMs. Obviously there is much subgrid-scale, topographically induced variability in snowpack dynamics. However, even grid-scale snowpack information, as provided currently by GCMs, is useful. Subgrid-scale modeling is possible from higher-resolution topographic and topoclimatological models, and the U.S. Soil Conservation Service operates a national Snow Survey Network (used for summer irrigation scheduling) of ground measurements for model development/validation.

Snowpack is a critical mechanism for water storage, providing summer water in arid regions and controlling flood potential in many wetter areas. Snowmelt is an important trigger of growing season, causing an intense burst of trace gases from the spring soil and hydrologic flushing of dissolved elements. Spring snowmelt initializes calculations of seasonal soil water depletion and ecosystem stress and produces primary annual hydrologic discharge in semiarid lands. Snowpack insulates soils from extreme temperatures, and is important in vegetation/crop survival.

Variables Linking Terrestrial Ecosystems to Atmospheric GCMs

Evapotranspiration

The single most important feedback from the land to the climate models is the partitioning of incident solar radiation (H) to sensible or latent heat (LE), the Bowen ratio (H/LE). This partitioning is controlled by the surface evapotranspiration in a complex fashion and is computed with soil-vegetation-atmosphere models. Major decreases in seasonal Bowen ratio occur as vegetation develops, increasing ET and latent energy. Later in the growing season, as vegetation either senesces or endures soil water deficits, physiological water stress and stomatal closure can cause Bowen ratios to increase by an order of magnitude as progressively more of the incoming energy produces sensible heat. This cannot be effectively simulated by meteorological measures alone, but can be calculated (interactively) in models of ecosystem water balance that determine

seasonal LAI, soil moisture, and water use efficiency as a function of climate, CO_2 concentrations, plant physiology, and other perturbations and stresses. Ecosystem water balances are typically executed on hourly or daily time scales.

Albedo

At minimum, ecosystem models predict seasonal phenology and assume some ecosystem structure and soils. A look-up table translation scheme can be used to yield broadband albedos for each of these ecosystem compartments, which can then be weighted to give the mean albedo for a GCM grid cell as a function of time. There are sophisticated models (e.g., ray tracing models) that calculate spectral reflectivities as a function of, among other things, leaf shape, orientation, and distribution. However, significant generalization of these models is needed before they are useful for GCM-scale applications. Inversion of satellite-derived surface reflectance can now provide global maps of surface albedo.

A major uncertainty in GCMs is the highly dynamic albedo changes caused by the delivery and melting of snow. Albedo varies with age (and depth) of snow and with the masking depth of vegetation. This introduces a large degree of uncertainty to the energy balance of high latitudes. Either mechanistic submodels of snowpack dynamics or regular reparameterizations of the GCM during simulations by satellite data are probably required to meaningfully improve this situation.

Roughness Length

Topographic roughness and vegetation height affect momentum dissipation at the surface. In general, topographic roughness dominates the momentum exchange. The improved spatial resolution of the NCAR CCM2 allows higher definition of grid-cell topography. However, additional improvement may be possible by using subgrid-scale information on topographic variation.

Typically, a roughness length is assigned to each vegetation type, ranging from around 0.02 to 6.0 m, small relative to topography. Models that simulate ecosystem transitions can, in principle, output roughness length as a function of time. How important this is for altering GCM circulation has not been established.

Greenhouse Gases

Models of canopy photosynthesis-respiration balances and soil carbon cycle dynamics in ecosystems by definition keep track of surface CO_2 uptake from the atmosphere by simulating the produc-

tion and return of CO_2 to the atmosphere through soil organic matter turnover. When applied to scenarios of climate change, these models project changes in the net fluxes of CO_2 that are useful for studies of the carbon cycle. A daily or longer surface CO_2 balance could in principle be entered into a GCM. Again, the primary problem is the spatial aggregation of the ecosystem model outputs to the GCM cell size. Alternatively, simple satellite-driven AVHRR/NDVI-based models have been highly correlated with CO_2 balance and could be implemented globally (Running and Nemani, 1988).

Carbon dynamics models can be adapted to the study of other trace gases. We envisage that a separate treatment would be required for each gas. N_2O and NO fluxes require elaboration in soil compartments and explicit treatment of soil moisture regimes. Isoprenes, terpenes, and other nonmethane hydrocarbons require some scaling to the metabolic function of certain vegetation species. Modeling of carbon monoxide must be linked to a fire model, and CH_4 requires a detailed hydrology model. Because of the many linkages required, global-scale modeling of trace gas fluxes is not currently possible.

Unmodeled Land Parameters Needed by GCMs

A number of soil and vegetation characteristics are needed for GCM surface parameterization, as exemplified by the biosphere-atmosphere transfer scheme (BATS; see Tables 2 and 3 in Dickinson et al., 1986). Many of these characteristics are not outputs of ecosystem models but are surface parameterizations also needed by them. Some of these parameters can be estimated globally, but many are impossible to do accurately. Satellite-derived estimates of vegetation cover and seasonal variation are available from weekly composite global AVHRR/NDVI maps. These can be translated reasonably well to maximum-minimum LAI for different biome types. Physiological parameters like minimum stomatal resistance or leaf light sensitivity cannot be directly inferred. Global albedo is now being monitored weekly by satellite and could be entered into the GCMs. Soil physical and hydraulic parameters cannot be monitored by satellite, and existing global soils maps are taxonomically based and of questionable accuracy. It is not clear how this problem can be improved (see Parton et al. report, this volume).

References

Dickinson, R.E., A. Henderson-Sellers, P.J. Kennedy, and M.F. Wilson. 1986. *Biosphere-Atmosphere Transfer Scheme (BATS) for the NCAR Community Climate Model.* Technical Note NCAR/TN-275, National Center for Atmospheric Research, Boulder, Colorado.

Dickinson, R.E., R.M. Errico, F. Giorgi, and G. Bates. 1989. A regional climate model for the western United States. *Climatic Change 15*, 383–422.

Liaw, Y.P., D.L. Sisterson, and N.L. Miller. 1990. Comparison of field, laboratory, and theoretical estimates of global nitrogen fixation by lightning. *Journal of Geophysical Research 95*, 22489–22494.

Liu, S., and R.J. Cicerone. 1984. Fixed nitrogen cycle. In *Global Tropospheric Chemistry: A Plan for Action*, National Academy Press, Washington, D.C., 113–116.

Logan, J.A. 1983. Nitrogen oxides in the troposphere: Global and regional budgets. *Journal of Geophysical Research 88*, 10785–10807.

Running, S.W., and R.R. Nemani. 1988. Relating seasonal patterns of the AVHRR vegetation index to simulated photosynthesis and transpiration of forests in different climates. *Remote Sensing of Environment 24*, 347–367.

Appendix: A Regression of Atmospheric Circulation to Local Weather

A critical gap in connecting atmospheric climate models to ecosystem models of the land surface lies in the provision of local estimates of surface precipitation and daily weather statistics. Atmospheric climate models are designed to operate on spatial resolutions of several hundred kilometers horizontally and 1000–300 millibars vertically, whereas ecosystem models are developed and tested on data relevant to a small watershed, typically of 1–10 km. The variables predicted explicitly in GCMs (pressure, temperature, moisture, and wind in the free atmosphere) relate to the atmospheric circulation on regional scales. The lowest atmospheric cell may be between 1000 and 950 mb and will not be representative of surface conditions without a boundary-layer submodel. Subgrid-scale topography, land cover, and lake effects can all have a major impact on local temperature and precipitation, particularly the daily maximum and minimum temperatures, the incidence of solar radiation, and the probabilities of rainfalls of different intensities, which are the variables needed to run ecosystem models. Although for biogeochemical purposes monthly averages are adequate, to simulate the hydrologic balance, daily data and a knowledge of the diurnal cycle are imperative. Successional models are sensitive not only to seasonal averages but also to disturbances such as unseasonal frosts and fires. Giving a general definition of disturbance is difficult, but the meteorological factors involved can all be derived from a good daily weather record. Though surface temperature, solar radiation, and rainfall are all computed hourly in a GCM as part of the treatment of the atmospheric boundary layer,

these are highly parameterized estimates on a scale of the GCM grid, and it is not obvious how to derive locally valid values.

A similar problem is encountered in weather prediction, in which model simulations of the atmospheric circulation have to be translated on a daily basis into specific local forecasts for transmission to the public. It is believed that changes in local weather are largely controlled, at least in a statistical sense, by the regional atmospheric circulation, so a widely used technique is to correlate over several years the values of a selected subset of variables in the weather prediction model with the daily record from a local weather station. The correlation table is then used, in conjunction with future values from the prediction model, to predict the local station's weather. This technique, known as model output statistics, has proved as skillful as most human forecasters using more subjective methods.

This approach could easily be adapted to translate the output of climate models into equivalent local climates. Running a climate model in forecast mode for many years is normally not practical; instead, the observed values of the regional-scale circulation variables required for the correlation may be taken from actual observations rather than from a forecast, using a daily weather analysis. Of course, it is not to be expected that subsequent application of this correlation table to the output of a climate GCM will automatically produce a good simulation of local climate if the GCM produces inadequate statistics of the regional circulation patterns. However, the exercise will certainly focus attention on which aspects of the GCM circulation are incorrect, and, in conjunction with a local ecosystem model, could lead to a figure of merit by which improvements in simulations of present climate and the significance of projected changes could be assessed.

An issue that at once arises in applying this approach is the availability of suitable data. In most regions of the world there are many weather stations recording daily maximum and minimum temperature, total rainfall, and hours of sunshine. However, long records of hourly precipitation are less readily available, and intensity of solar radiation (as opposed to the more qualitative surrogates of cloudiness and hours of sunshine) is measured at only a few stations. However, surface solar radiation can be inferred fairly directly from geostationary satellite measurements of solar reflectance. Corrections must be made for variations in viewing angle, for surface albedo, and for absorption of solar radiation within clouds and other aerosols, and the results must be calibrated against the available surface radiation measurements. Once this is done, the data required are widely available over most, though not all, of the world.

Another issue is whether the structural relations between a given regional circulation pattern and local weather are likely to be stable under conditions of changing climate. To the extent that these connections are controlled by the interactions of topography, wind direction, and temperature through the troposphere, changes are indeed likely to be caused by changes in frequency of a regional-scale pattern and allowed for in this methodology. To the extent that they depend upon changes in aerosol or cloud condensation nuclei, which are not discussed in routine weather analyses, the correlation tables would change over decades. Indeed, systematic trends observed in such correlation tables might be the best indicators of this type of climate change.

It is also clearly inadequate to be able to estimate local climates only at points where there are weather station records. Modeling of the effects of topography and other causes specific to the local weather station is clearly an integral part of any application. This modeling may be empirical or may be based on more sophisticated local process studies using dynamical mesoscale models for phenomena such as lake effects and mountain drainage. In some locations such studies are already going on for reasons other than climate change, but it is important to generalize this experience to a global scale.

There are also extreme events of great importance to certain ecosystems, such as hurricanes and tornados, of which the frequency may well change with climate regime. Yet these events are not predicted within present climate models. Because of their rarity, such events are unlikely to appear in daily correlation tables, though special studies might well reveal the regional circumstances under which they are most likely to occur. GCM simulations should then be examined for changes in hurricane and tornado potential, which would be fed off line into ecosystem models.

If applied to a suitable sample of weather stations within a region, the correlation technique would also provide data sets to test and validate the physically based parameterizations of the surface variables predicted in the climate model for the purpose of keeping track of the surface energy and moisture balance. Indirectly, these parameterizations depend on the same regional atmospheric variables. It is, of course, straightforward to produce similar correlation tables within the climate model itself. It could be argued that it is inconsistent to maintain within the same framework two distinct connections between regional circulation variables and surface climatology and water balance, one empirical and site-specific, the other physically based but highly parameterized. In the long run this argument is probably correct, but until more experience has been gained the dualism is likely to be a source of strength.